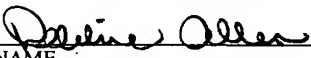


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APPLICATION FOR LETTERS PATENT

FOR

**SELECTIVE BASE ETCHING**

This application claims priority to Swedish Application No. 0102560-0 filed July 18, 2001 and Swedish Application No. 0103980-9 filed November 28, 2001

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## SELECTIVE BASE ETCHING

### Cross Reference to Related Application

[0001] This application is a continuation of copending International Application No. PCT/SE02/01361 filed July 9, 2002 which designates the United States, and claims priority to Swedish application no. 0102560-0 filed July 18, 2001 and Swedish application no. 0103980-9 filed November 28, 2001.

### Technical Field of the Invention

[0002] The present invention relates to a method of etching selectively when manufacturing a semiconductor device and to a method in the manufacturing of a bipolar transistor while applying said method of etching selectively.

### Description of the Related Art

[0003] The trend in design and manufacture of integrated circuits leans towards progressively smaller individual components of progressively higher performance. The dimensions of bipolar transistors are e.g. becoming progressively smaller, both horizontally and vertically, so as to increase the packing density and transistor speed. The manufacturing precision has therewith become progressively more important, both with regard to individual process steps and with regard to alignment of different layers.

[0004] In the manufacture of bipolar high frequency transistors there is today normally used a technique that employs a self-registered base-emitter structure (T. H. Ning et al. "Self-aligned npn bipolar transistors" IEDM Techn. Dig., pages 823-824, 1980), which enables the transistor cell to be made smaller while obtaining a reduced base collector capacitance and a reduced base resistance when the extrinsic base is connected to the intrinsic base in the immediate proximity of the emitter. Several variants of this method are known in the art.

[0005] US 5,266,504 describes a method of manufacturing a self-registered bipolar transistor, in the which the base is grown epitaxially and the emitter is formed by deposition of an amorphous silicon layer followed by deposition of a polycrystalline silicon layer, whereafter the structure is patterned and etched. The amorphous silicon layer is then recrystallized by SPE (Solid Phase Epitaxy). This method is able to provide a thin base and a sharp and well-controlled emitter-based junction.

[0006] US 4,988,632 teaches deposition of a polycrystalline or amorphous silicon layer on a substrate and doping of the layer. A layer of LTO (Low Temperature Oxide) or some other dielectric is deposited on said silicon layer, whereafter the structure is patterned and etched to provide a base electrode and emitter opening. In US 5,213,989 is discussed that a layer, which may be of polycrystalline silicon, amorphous silicon or another silicon-based material, is deposited on a substrate and doped, whereafter a dielectric layer, preferably a TEOS-based (Tetra Ethyl Ortho Silicate-based) oxide is deposited over the silicon layer. The structure is patterned and etched in a known manner.

[0007] Those problems that occur when etching selectively a polycrystalline silicon layer from a silicon substrate involve difficulties in stopping the etching process so that the polycrystalline silicon layer is removed completely without etching the substrate too deeply. In US 5,616,508 is depicted how this problem can be reduced by introducing an etch-stopping layer in the structure so that the etching can be stopped in a first step towards the etch-stopping layer, whereafter further etching carefully removes the etch-stopping layer to reach the silicon substrate. In US 5,502,330 this concept is further developed by employing a further etch-stopping layer.

[0008] A further aspect is that the polycrystalline silicon layer is etched with different rates along different crystal directions and in grain boundaries resulting in

etching residues, so-called pillars, or in irregularities in the etch surface, so-called facets, and in blunt or dull edges in the etched openings. There are also other aspects on polycrystalline silicon layers, which are discussed in WO-9719465 and in US 6,077,752 and it is disclosed therein the advantages obtained by selecting the deposited silicon layer structure to be amorphous. Such silicon lacks crystal structure and in such a manner many of the problems and drawbacks in the use of polycrystalline silicon are removed.

[0009] Nevertheless the etching selectivity for etching amorphous silicon on monocrystalline silicon may in some instances be too low. Typically, a certain degree of overetching down into the substrate is allowed but in the manufacture of bipolar transistors having an epitaxially formed base such overetching is not allowed and, thus, the etching selectivity may be insufficient.

#### Summary of the Invention

[0010] The object of the present invention is to resolve the above problems and thus being able to produce semiconductor components, particularly bipolar transistors, of higher quality and/or higher performance and/or of smaller size than those semiconductor components produced by hitherto known methods.

[0011] To this end the inventive method includes the etching of deposited silicon-germanium layers, which have high selectivity towards monocrystalline silicon. Thus, many of the problems and drawbacks of etching polycrystalline or amorphous silicon on monocrystalline silicon are removed.

[0012] The inventive method involves forming a layer of silicon-germanium on a crystalline silicon substrate, which may be a bulk substrate, optionally with one or several epitaxial layers formed thereon, and optionally being doped and/or containing germanium.

[0013] The silicon-germanium layer is deposited preferably by UHV-CVD (Ultra High Vacuum-Chemical Vapor Deposition), RP-CVD (Reduced Pressure-Chemical Vapor Deposition) or MBE (Molecular Beam Epitaxy). The silicon-germanium layer can be formed by simultaneous deposition of silicon and germanium or by deposition of silicon and a subsequent implantation of germanium. Preferably, the silicon-germanium layer formed has a germanium content of between 5 and 60%, more preferably between 10 and 55% and most preferably between 30 and 50% (the percentages denote atomic percentages). Further, the silicon-germanium layer may be formed as a multilayer structure, wherein each layer has an individual material composition and possibly doping.

[0014] Further, according to the invention a protecting layer of a dielectric is deposited onto this silicon-germanium layer. Preferably, the dielectric is deposited by any of the following methods: PE-CVD (Plasma Enhanced Chemical Vapor Deposition), SA-CVD (Sub Atmospheric Chemical Vapor Deposition), HDP-CVD (High Density Plasma Chemical Vapor Deposition), MBE or with the aid of a spin-on technique. The dielectric layer is preferably comprised of PETEOS (Plasma Enhanced Tetra Ethyl Ortho Silicate).

[0015] The resultant structure is patterned, whereafter the dielectric layer and the silicon-germanium layer are etched, preferably dryetched, within a predetermined area. During the etching, end point detection of germanium, e. g. performed by means of emission spectroscopy, may be performed to accurately control the etching of the silicon-germanium layer.

[0016] Preferably, the silicon-germanium is deposited at a temperature such that the layer is deposited as an amorphous layer, whereby the dielectric layer is deposited onto the amorphous silicon-germanium layer in such a manner that the amorphous layer does not crystallize. Subsequent to etching the structure may be heat-treated so that the amorphous layer crystallizes.

[0017] The inventive etching method provides structures, which have sharply defined edges and smooth pronounced etch surfaces in absence of pillar or facet formation tendencies. Further, good etching selectivity between the silicon-germanium and the crystalline silicon is obtained. This results in semiconductor components of improved performance in relation to earlier produced semiconductor components.

[0018] Particularly when manufacturing a bipolar transistor having a self-registered base emitter structure the above etching process can be employed when etching the emitter opening and in such a manner semiconductor devices of very small dimensions (length scales in the submicrometer range) can be produced. The advantages obtained with the present method include good etching selectivity when etching silicon-germanium on crystalline silicon, good CD control (Critical Dimension control), i. e. good control of the dimensions of the etched emitter opening, and avoidance of the risk for channeling of dopants.

[0019] Silicon-germanium may advantageously also be employed as a material for integrated resistors on the surface of the integrated circuit.

#### Brief Description of the Drawings

[0020] The invention will now be described more in detail with reference to the accompanying drawings, in which Figs. 1 and 2 are cross-sectional views illustrating two inventive method steps when etching a silicon-germanium layer on a silicon surface, and Figs. 3-6 are cross-sectional views illustrating four inventive method steps during the manufacture of a bipolar transistor having a self-registered base emitter structure, starting from the structure illustrated in Fig. 2.

#### Detailed Description of the Preferred Embodiments

[0021] Shown in Fig. 1 is a silicon substrate 1, wherein the silicon may be monocrystalline, polycrystalline or microcrystalline but is preferably monocrystalline. As in Fig. 1 the substrate 1 may have various defined regions 2-5, which will be

described below more in detail. Such regions may include a doped region, particularly a region doped with boron, and/or a region containing germanium. The substrate may alternatively be homogeneous. Any surface oxide present on the substrate 1, possibly having a thickness of some nanometers, can be removed by conveniently dipping the substrate in an HF bath or in an HF vapor.

[0022] In accordance with the invention there is deposited a layer 6 of silicon-germanium on the substrate 1 to a thickness of some hundreds of nanometers, preferably by employing RP-CVD technique typically in a temperature interval of 500-550 C. The exact temperature to achieve the desired layer structure will depend on the germanium concentration and level of in-situ doping of dopants. The silicon-germanium may alternatively be deposited at another temperature and/or by employing some other technique, such as UHV-CVD or MBE. In order to achieve good etching selectivity a proportionally high germanium content (30-50 atomic percent) in the layer is preferably selected. The silicon-germanium layer is preferably deposited as an amorphous layer but may alternatively be deposited as a polycrystalline layer. Conveniently, silicon and germanium are deposited simultaneously but alternatively a silicon layer, with thickness of some nanometers, may first be deposited as a "seed layer", whereafter a silicon-germanium film is the deposited. Still another alternative is to first deposit a silicon layer, whereafter germanium is implanted into the silicon layer.

[0023] References discussing deposited layers of  $\text{Si}_x\text{Ge}_{1-x}$  include i. a. King et al., IEDM Tech Dig. 1990, p. 25, E. Josse et al., Proc. ESSDERC 2000, Babcock et al., IEEE Electron Device Letters. p. 283, June 2000 and US 5,592,017. The former documents relate to the use of silicon-germanium in the manufacture of MOS transistors and the latter one discusses silicon-germanium for resistors in integrated circuits. The above documents are hereby incorporated by reference.

[0024] The silicon-germanium layer 6 may optionally be doped. Most advantageously, the silicon-germanium layer is deposited containing p-type dopants. The available deposition techniques easily admit that the layer can alternatively consist of a stack of different layers having different material composition and dopants.

[0025] It is alternatively possible to dope through ion implantation, wherein, by the choice of amorphous silicon-germanium, channeling of the dopant in grain boundaries and crystal directions is avoided. Typical p-type dopants suitable for ion implantation are in this instance B<sup>11</sup> or BF<sub>2</sub>.

[0026] In accordance with the invention there is deposited on the silicon-germanium layer 6 a protective dielectric layer 7. If the silicon-germanium layer 6 is amorphous the protective dielectric layer 7 is deposited so as to prevent crystallization of the silicon-germanium layer 6. This is ensured when the dielectric layer 7 is deposited at a temperature of about 400°C and during a relatively short period of time. The so-called single wafer technique is preferably used in this regard, i. e. a technique in which one wafer is processed at a time, which gives shorter deposition times. Examples of such techniques at present are PE-CVD, SA-CVD, HDP-CVD, MBE and the spin-on technique.

[0027] The dielectric layer 7 may be comprised of a nitride or an oxide, although it will preferably be a silicate. Conveniently, the silicate is PETEOS, i. e. TEOS (Tetra Ethyl Ortho Silicate), deposited by PE-CVD. This results in a high quality layer of low particle density and porosity and also affords a good control over the layer thickness. The dielectric layer 7 shall be deposited to a thickness in the order of some hundreds of nanometers. A preferred deposition temperature is between 250 and 400°C. Although not shown, one or more additional dielectric layers may be deposited on the structure.



[0028] The structure, referenced 8 in Fig. 1, is then patterned by a conventional photolithographic process, whereafter the possibly superimposed additional dielectric layers (not shown), the dielectric layer 7 and the silicon-germanium layer 6 are removed within a predetermined region or area 9 in an etching step. The upper side of the substrate 1 is thus exposed within the region 9.

[0029] The dielectric layer 7 may be etched using an anisotropic dryetching process, e.g. using a  $\text{CHF}_3/\text{O}_2$  or a  $\text{C}_2\text{F}_6$  plasma. The silicon-germanium layer 6 is preferably etched according to the invention by a dry-etching process, which may be anisotropic, e.g. using an HBr and/or  $\text{Cl}_2$ -based plasma, but preferably using an  $\text{SF}_6/\text{O}_2$  plasma or alternatively an  $\text{SF}_6/\text{HBr}$  plasma, which results in a very good selectivity towards underlying layers.

[0030] If the silicon-germanium layer is amorphous, it lacks macroscopic crystal structure, is rich in defects and has therefore greater free energy than polycrystalline and monocrystalline silicon. It is thus possible to achieve good etching selectivity between amorphous material and monocrystalline silicon, see US 6,077,752.

[0031] It is possible to etch away all amorphous silicon-germanium without etching deep down into the substrate. When etching amorphous silicon-germanium no undesirable etching is obtained along grain boundaries or crystal surfaces, therewith resulting in smooth etched surfaces. When overetching the underlying monocrystalline silicon, a smooth surface is obtained in the absence of replica of the grain structures, so-called reproduction of facets or crystal grains or residual crystal grains, so-called pillars, as would possibly be the case when etching polycrystalline or microcrystalline silicon. Furthermore, an opening that is etched out in amorphous silicon-germanium will have sharper edges and smoother sidewalls than the corresponding opening that is etched out in polycrystalline silicon. It is highly important to achieve good CD control, i.e. control over the dimensions of the etched opening, particularly when

manufacturing semiconductor devices within the submicrometer range, such a control being achieved when etching in amorphous silicon-germanium.

[0032] Nevertheless, there is in many applications a satisfactory etching selectivity also between polycrystalline silicon-germanium and monocrystalline silicon.

[0033] Another method to improve etching selectivity is to use end-point detection. The length of the dry-etching process, i.e. the etching time, for the etching of the silicon-germanium layer 6 can be determined by means of optical spectroscopy (so called end-point detection) in real time by monitoring emission lines from the etching plasma.

[0034] When the silicon-germanium layer 6 is etched away, particularly in a reactive ion etch (RIE), chemical reactions of the gases in a plasma take place, which produce ions that are accelerated towards the semiconductor surface. Germanium, which is etched away, takes part in these reactions and as a result volatile germanium compounds are formed, which are transported away from the semiconductor surface. When germanium is no longer detected, the semiconductor surface is free from germanium and the endpoint is found. End-point detection is described in e.g. S. Wolf and R. N. Tauber, "Silicon Processing for the VLSI Era, Volume 1 - Process Technology" pp. 565-568, Lattice Press, Sunset Beach, 1986, which text hereby is incorporated by reference.

[0035] Possibly, the etching is continued a short additional time after the end-point has been detected in order to safeguard that the silicon-germanium layer 6 is etched away completely. Typically, such time period last a couple of seconds. Nevertheless, a much less degree of overetching may be performed using end-point detection than if a conventional time-based etching would be performed (etching during a predetermined time period based on layer thickness and estimated etching

rate, to which 15-30% additional time is added to make sure that the layer is removed completely).

[0036] End-point detection is preferred in this respect since a better control of the etching process is obtained. Further, end-point detection requires less prior knowledge of the structure to be etched and of the etch rate. Thus, end-point detection is better to manage variations in layer thickness and in etching parameters.

[0037] Further, as an alternative to continue etching a short additional time after the end-point has been detected in order to safeguard that the silicon-germanium layer 6 is etched away completely, the structure may be etched a short time using a wet etch chemistry.

[0038] Still further, the end-point detection can additionally or alternatively be used to trigger an alteration of applied etching conditions, such as pressure, gas composition, and bias, to achieve a higher selectivity in the process.

[0039] The process of using end-point detection can be used in yet another manner if the deposited SiGe-layer 6 contains a stack of multiple silicon layers, with a thin layer containing germanium close or closest to the interface where the etching is to be stopped, i.e. the substrate surface. This layer may have a thickness of only a few tens of nanometers, and may contain a large fraction of germanium (typically in the order of 30%). On top of this layer, a thicker layer of silicon, optionally containing p-type dopant such as boron, as discussed above, is deposited.

[0040] During etching, a distinct germanium compound signal, using the previously described end-point detection system, will be achieved when the etching reaches down to the thin layer containing germanium. The etching will preferably be continued until the germanium compound signal declines (possible with some additional etching time before the etching is stopped).

[0041] The purpose of the thin Ge-layer is thus to function as a "marker" to indicate that the etching has reached the desired level in the multilayer stack.

[0042] According to the invention the above-described method steps can be used as a subprocess in the manufacturing of an npn-bipolar transistor having e. g. a self-registered base emitter structure.

[0043] The method of manufacturing a bipolar transistor starts from the structure illustrated in Fig. 2 having defined regions 2-5, i.e. as seen from the bottom a p-doped region 2, an n<sup>+</sup>-doped layer 3 for a collector electrode and nearest the surface an n-doped layer 4, which is surrounded by an electrically insulated region.

[0044] The window 9 shown in Fig. 2 will form an emitter opening, whereas the amorphous or polycrystalline silicon-germanium layer 6 will form an extrinsic base. The silicon-germanium layer may alternatively be formed simultaneously outside component areas on top of field oxide regions (such as those referenced 5 in Figs. 1 and 2) for use as resistances having low temperature dependence (low T<sub>c</sub>).

[0045] As shown in Fig. 3 there is then grown on the structure shown in Fig. 2 a thin thermal oxide layer 10 having a thickness of one or some tens of nanometers at such a temperature which would cause the silicon-germanium layer 6 if was amorphous to crystallize. Alternatively, the oxide layer is deposited as a TEOS, if so needed. The crystalline silicon-germanium layer is referenced 6' in Fig. 3. A suitable temperature range is in this regard 700-900°C. Parallel herewith dopants are driven into the substrate 1 from the doped crystalline silicon-germanium layer 6' to the formation of a doped region 11. A p-doped intrinsic base 12 is formed by ion implantation of e. g. B in the substrate 1 through the thin oxide layer 10. Alternatively, an epitaxially formed base layer may already exist on the wafer and in such a case no further implantation is needed. The p<sup>+</sup>-doped region 11 enables an electrical contact between the intrinsic base 12 and the extrinsic base 6' to be obtained.

[0046] A layer 13 of an electrically insulating material is then deposited conformly over the structure of to Fig. 3. The layer 13 will preferably have a thickness of some hundreds of nanometers and will preferably consist of a nitride, e. g. silicon nitride,  $\text{Si}_3\text{N}_4$ , and be deposited by LP-CVD technique (Low Pressure Chemical Vapor Deposition). The resultant structure is shown in Fig. 4.

[0047] The nitride layer 13 is re-etched anisotropically in a plasma etching process until a thin oxide layer (not shown) remains on top of the substrate 1 in the emitter opening 9. A nitride string or a so-called nitride spacer 13 remains along the sidewalls of the emitter opening 9. The thin oxide layer (not shown) is then removed by a selective plasma etching process or a wet etching process, therewith exposing the substrate surface 14 in the emitter opening. The resultant structure is shown in Fig. 5. This structure is then dipped optionally in an HF bath or in an HF vapor to remove surface oxide; whereafter an emitter layer (not shown) of polycrystalline or amorphous silicon is deposited on the structure shown in Fig. 5. The emitter layer is deposited preferably to a thickness of some hundreds of nanometers and is  $\text{n}^+$ -doped, either in-situ during deposition, or later e. g. by implanting arsenic. The structure is then heat-treated, wherein the dopant (arsenic) is driven into the substrate 1 and forms an  $\text{n}^+$ -doped region 16. During the heat treatment boron diffuses down into the substrate, wherewith the extrinsic base becomes somewhat deeper, as appears from the region referenced 11' in Fig. 6. A very shallow emitter ( $\text{n}^+$ )-base (p) junction can be obtained by carrying out the method steps with precision and by carefully controlling the steps. The emitter layer (not shown) is patterned lithographically and plasma-etched in a conventional manner to define an emitter 15 in the emitter opening 9 as shown in Fig. 6.

[0048] A further oxide layer is then optionally deposited on the structure shown in Fig. 6, whereafter the structure is patterned and etched to form contact holes.

[0049] It will be understood that the method described above can also be used in the manufacture of pnp transistors after changing the dopants. In this regard the silicon-germanium layer 6 and the intrinsic base 12 are then n-doped, whereas the collector 3, 4 and the emitter 15, 16 are p-doped.

[0050] Further, as an alternative to the formation of a p-doped intrinsic base 12 by ion implantation, the intrinsic base may, according to the present invention, be formed in a conventional SiGe-base process flow, see e.g. D. L. Hame et al., "Si/SiGe Epitaxial Base Transistors - Part II: Process Integration and Analog Applications", IEEE Transaction on Electron Devices, p. 469, Vol. 42, No. 3, 1995, whereafter the extrinsic base is formed as described above. The article by Hame et al. is hereby incorporated by reference.

[0051] As still a further alternative to the formation of a p-doped intrinsic base 12 by ion implantation of e.g. boron in the substrate 1 through the thin oxide layer 10, a mesa type of transistor may be formed. For additional details regarding such a transistor structure reference is given to our co-pending Swedish patent application No. 0103726-6 entitled "Silicon-germanium mesa transistor" and filed on November 9, 2001, which application being hereby incorporated by reference.

[0052] The advantages that are afforded by the inventive method as described above include greater precision in the manufacture, the possibility of reducing dimensions, meaning lower base collector capacitance and lower base resistance of the transistor, and the avoidance of the risk of poor or no electrical contact between the intrinsic and extrinsic bases, as the emitter opening may be etched without the need of a powerful overetching procedure.